Comparison of supplemental lighting from high-pressure sodium lamps or light-emitting diodes on morphology and nutrient uptake of greenhouse crops

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Abstract

Supplemental lighting in greenhouses augments ambient sunlight, especially during winter and spring production to provide sufficient irradiance for desired growth. Light-emitting diodes (LEDs) are increasingly used in place of high-pressure sodium (HPS) lamps, but growers are hesitant to switch due to price and concerns about spectral effects on growth, morphology, and nutrient uptake. Eight greenhouse crops [basil (*Ocimum basilicum* 'Genovese Emily'), geranium (*Pelargonium ×hortorum* 'Maverick Red'), pansy (*Viola ×wittrockiana* 'Delta Premium Blue Blotch'), pepper (*Capsicum annuum* 'California Wonder'), spinach (*Spinacia oleracea* 'Whale'), tomato (*Solanum lycopersicum* 'Early Girl'), vinca (*Catharanthus roseus* 'Cora Burgundy), and zinnia (*Zinnia marylandica* 'Zahara Cherry')] were grown in a glass greenhouse and provided a supplemental photosynthetic photon flux density of 100 µmol m^{-2} s^{-1} 14 h day^{-1} from HPS or LED (50 blue:50 red:22 far-red) fixtures. Plants receiving supplemental LED lighting were 11-99% taller, 4-45% wider, and had 25-143% greater dry mass than plants receiving supplemental HPS lighting. Relative chlorophyll content was 102% higher in LED-supplemented basil, but 5-26% lower in the other seven species, compared to HPS-supplemented plants. Foliar nutrient concentrations of LED-supplemented plants were 2% higher to 14% lower (nitrogen), 10% higher to 20% lower (phosphorus), 3-32% lower (potassium), 15% higher to 9% lower (calcium), 28% higher to 12% lower (magnesium), 11% higher to 18% lower (sulfur), 30% higher to 18% lower (boron), 23% higher to 34% lower (copper), 2-40% lower (iron), 13-41% lower (manganese), and 14% higher to 31% lower (zinc), relative to HPS-supplemented plants.

Keywords: controlled environment agriculture, floriculture, light quality, ornamental plants

INTRODUCTION

Supplemental lighting provided to greenhouse crops during winter and spring production augments ambient solar radiation to provide a daily light integral (DLI; mol m^{-2} d^{-1}) sufficient for desired crop growth, development, and morphology. High-intensity discharge (HID) lamps [e.g., high-pressure sodium (HPS) or metal halide (MH)] are the predominant supplemental light source in greenhouses. A 2017 US. Dept. of Energy report estimated the technology mix in greenhouses to be 98% HID lamps and 2% light-emitting diodes (LEDs), compared to 66% adoption of LEDs for sole-source lighting applications in indoor vertical farms (Stober et al., 2017). Benefits of LEDs include less radiant heat emission and therefore close canopy installation if desired, instantaneous on/off capability that does not impact operating life, narrow waveband selection, adjustment of radiation intensity through dimmable drivers, and a lower operating electrical capacity (Runkle et al., 2019). However, high capital costs and a lengthy return on investment have impeded their installation in new projects and the replacement of existing HPS lamps with LED fixtures. Additionally, limited research comparing HPS lamps and LED fixtures for supplemental greenhouse lighting have delayed adoption. Growers have concerns regarding the spectral

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effects on growth, morphology, and nutrient uptake of container-grown ornamentals and vegetables.

A few studies (Collado et al., 2018; Craver et al., 2019; Currey and Lopez, 2013; Hernández and Kubota, 2015; Poel and Runkle, 2017a, b; Randall and Lopez, 2015) have compared HPS and LED light sources for supplemental greenhouse lighting during young plant production. In general, cuttings or seedlings supplemented with light from HPS lamps were of similar or increased growth and quality relative to those grown under LEDs, but this was dependent on species, cultivar, and LED spectrum. Very few studies have compared the finished production stage of containerized greenhouse crops grown under supplemental HPS or LEDs (Craver et al., 2019). Additionally, studies often report growth (e.g., shoot and root dry mass), morphogenesis (e.g., height, leaf area, stem caliper), days to flower, and/or secondary metabolite accumulation (e.g., pigmentation, antioxidant capacity) (Bantis et al., 2018), but very few examined the impact of light source on plant nutrient status (Craver et al., 2019). Therefore, our objective was to evaluate growth, morphology, and nutrient status of eight species (four ornamental, three vegetable, and one culinary herb) grown with supplemental HPS or LED radiation.

MATERIALS AND METHODS

Four-week-old seedlings of basil (*Ocimum basilicum* 'Genovese Emily'), pepper (*Capsicum annuum* 'California Wonder'), vinca (*Catharanthus roseus* 'Cora Burgundy), and zinnia (*Zinnia marylandica* 'Zahara Cherry') were transplanted on 1 Oct. 2015, and geranium (*Pelargonium* ×*hortorum* 'Maverick Red'), pansy (*Viola* ×*wittrockiana* 'Delta Premium Blue Blotch'), spinach (*Spinacea oleracea* 'Whale'), and tomato (*Solanum lycopersicon* 'Early Girl') were transplanted on 10 Nov. 2015 into 11.4-cm containers filled with a soilless substrate (LC-1; SunGro Horticulture, Agawam, MA, USA). Plants were grown in a glass-glazed greenhouse (41.7°N) for 4-6 weeks and provided supplemental lighting (100 µmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) for 14 h day^{-1}) from either 1000-W HPS lamps (Osram Sylvania Products, Inc., Manchester, NH, USA) or LEDs (GreenPower Research Modules, Philips, Eindhoven, The Netherlands). The HPS lamps provided a total photon flux density (TPFD; µmol m^{-2} s^{-1}) of 6 blue (B), 41 red (R), and 10 far-red (FR), and the LEDs provided a TPFD of 51 B, 50 R, and 22 FR (peak wavelengths at 451, 659, and 738 nm, respectively; Figure 1) based on spectroradiometer scans. There were 8 replicates per lighting treatment per species. Plants were fertigated as needed with 150 mg L^{-1} N continuous liquid fertilization (20N-4.4P-16.6K; J.R. Peters Inc., Allentown, PA, USA). Day and night air temperature set points were 21.1 and 18.3°C, respectively. Mean temperatures and DLIs are in Table 1. Leaf temperatures were measured 2 weeks after transplant using an infrared thermometer (Fisher Scientific, Fair Lawn, NJ, USA). At 4 or 6 weeks after transplant, plant height and width, node number, leaf diameter, and relative chlorophyll content (CCM-200; Apogee Instruments, Logan, UT, USA) were measured. Plants were harvested for determination of dry mass and mineral nutrient content using a CN analyzer (N; vario Microcube, Elementar, Hanau, Germany) or inductively coupled plasma optical emission spectroscopy (P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo, and Zn; iCAP 6300 Duo, Thermo Electron, Corp., Waltham, MA, USA) using methods described in Boldt et al. (2018). Due to differences in transplant date and harvest interval, data for each species were analyzed as t-tests (SAS9.3, SAS Institute, Cary, NC, USA), with significance at $P \leq 0.05$.

RESULTS AND DISCUSSION

Plants grown with supplemental LEDs were generally taller (11-99%; $P \leq 0.05$ for 7 of 8 species) and wider (4-45%; $P \leq 0.05$ for 6 of 8 species), with a greater dry mass (25-143%; $P \leq 0.05$ for all species), than plants supplied supplemental HPS (Table 2). Leaf diameter of tomato, pepper, and spinach grown under supplemental LEDs was 13, 18, and 22% wider, respectively, compared to HPS-supplemented plants. The increase in plant height and leaf diameter likely resulted from the additional FR light provided by the LED fixtures. This decreased the R:FR ratio, relative to the HPS treatment, and induced a shade avoidance response (Franklin and Whitelam, 2005). The additional FR from the LEDs also likely increased the quantum yield of photosystem I and increased net photosynthesis (Zhen and van Iersel, 2017). Although the two treatments had similar PPFDs (400-700 nm), the TPFD (400-800 nm) was ≈13 µmol m^{-2} s^{-1} greater in the LED treatment and likely contributed to the higher dry mass observed.

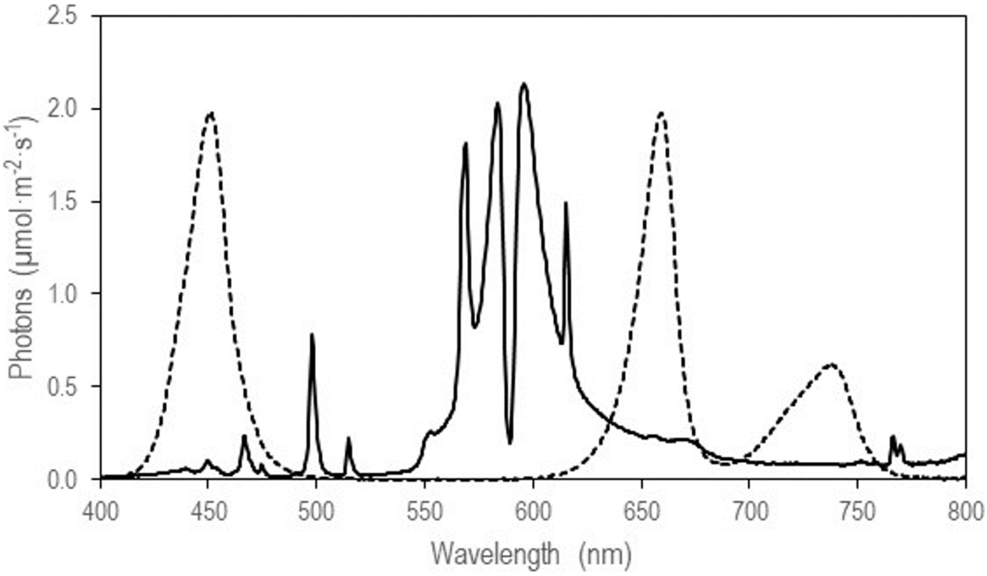

Figure 1. Spectral distribution of high-pressure sodium (solid line) and light-emitting diode (dashed line) fixtures used as supplemental lighting sources.

High-pressure sodium lamps emit substantial radiant heat, which can increase leaf and meristem temperatures (Faust and Heins, 1997; Mattson and Erwin, 2005) and increase rates of development (e.g., leaf unfolding and flowering) in plants grown beneath them. Many growers have hesitated to switch from HPS to LED fixtures due to high capital costs and because they do not wish to lose the radiant heat from HPS lamps, especially during winter (pers. observation). In this study, however, leaf temperatures of HPS-supplemented plants ranged from 1.7°C higher to 0.6°C lower 2 weeks after transplant, and statistically they were higher than LED-supplemented plants for three species (basil, pepper, and spinach), similar for four species (geranium, pansy, tomato, and vinca), and lower in one species (zinnia). Likewise, node number was unaffected by supplemental light source for six species (P>0.05) and differed by one node in basil and vinca (data not shown). Therefore, the reduced radiant heat emitted by the LEDs in this study did not consistently impact leaf temperature or delay leaf unfolding.

Time to flower is a critical metric to ensure crops are ready within the scheduled timeframe and to maximize sell-through at retail. Although we did not achieve complete flowering in this study prior to harvest, we did observe a greater percent flowering in most of the ornamental crops grown under supplemental LEDs. In the LED treatment, 0, 30, 67, and 80% of geranium, zinnia, pansy, and vinca flowered, respectively, compared to 0% of geranium, zinnia, and pansy, and 20% of vinca grown with HPS supplementation (data not shown). Flower initiation can be light quality-dependent, especially in photoperiodic crops. The additional FR radiation in the LED treatment (and corresponding decrease in R:FR ratio) likely promoted flower initiation in pansy, a long-day plant (Craver et al., 2018; Runkle and Heins, 2003). The rate of progress toward flowering (1/days to flower) is primarily influenced by temperature and, to a lesser extent, light intensity. In our study, leaf temperature of these four species varied by ≤0.6°C between lighting treatments and DLI varied by ≤0.5 mol m^{-2} d^{-1}, which may have been enough to hasten flowering in vinca and zinnia, both day-neutral species, under LEDs compared to HPS supplementation.

Table 1. Mean day and night air temperature, daily light integral (DLI), and percent contribution of supplemental high-pressure sodium (HPS) or light-emitting diode (LED) lighting to DLI.

Transplant	Day air temp (°C)		Night air temp (°C)		DLI (mol m^{-2} d^{-1})		Percent DLI from supplemental lighting	
	HPS	LED	HPS	LED	HPS	LED	HPS	LED
Group 1[a]	23.3±2.1	23.3±2.2	18.7±0.9	18.4±0.9	7.9±0.8	8.4±1.2	64.7±6.5	60.9±8.3
Group 2a[b]	21.1±1.2	20.7±1.4	19.3±1.1	18.7±1.1	6.6±0.5	6.9±0.6	76.7±5.5	73.4±6.0
Group 2b[c]	21.1±1.2	20.5±1.3	19.3±1.1	18.6±1.2	6.5±0.5	6.8±0.5	78.5±5.7	74.2±5.3

[a]Basil, pepper, vinca, and zinnia (Transplant 1; harvested 4 weeks after transplant, WAT).

[b]Tomato (Transplant 2; harvested 4 WAT).

[c]Geranium, pansy, and spinach (Transplant 2; harvested 6 WAT).

Table 2. Plant growth and leaf temperature (2 weeks after transplant) of 8 ornamental crops grown in a greenhouse and provided supplemental lighting from either high-pressure sodium (HPS) lamps or light-emitting diode (LED) arrays (50 blue:50 red:22 far-red) for 14 h day^{-1} at a photosynthetic photon flux density of 100 μmol m^{-2} s^{-1}.

Crop	Lighting	Plant height (cm)	Plant diam. (cm)	Leaf diam. (cm)	Dry mass (g)	Leaf temp (°C)
Basil 'Genovese Emily'	HPS	15.6±1.4	12.2±0.6	9.4±0.7	0.72±0.08	20.1±0.3
	LED	26.7±2.9 **[a]	15.5±0.6 **	10.4±0.3 NS	1.70±0.20 ***	18.4±0.2 ***
Geranium 'Maverick Red'	HPS	13.9±0.5	19.9±0.5	10.7±0.2	1.41±0.07	17.4±0.2
	LED	16.6±0.7 **	23.8±0.5 ***	10.5±0.2 NS	2.01±0.13 ***	17.0±0.2 NS
Pansy 'Delta Premium Blue Blotch'	HPS	6.6±0.3	11.6±0.6	3.9±0.2	0.70±0.09	18.6±0.2
	LED	12.0±0.4 ***	16.8±0.8 ***	4.4±0.1 NS	1.52±0.14 ***	18.9±0.1 NS
Pepper 'California Wonder'	HPS	17.7±0.9	23.9±1.1	6.6±0.1	1.54±0.11	20.2±0.1
	LED	35.3±1.1 ***	33.3±1.4 ***	7.8±0.3 **	2.94±0.16 ***	19.2±0.1 ***
Spinach 'Whale'	HPS	7.4±0.4	29.0±1.0	5.9±0.2	2.41±0.06	20.4±0.1
	LED	8.2±0.6 NS	30.3±0.8 NS	7.2±0.1 ***	3.04±0.20 **	19.6±0.2 **
Tomato 'Early Girl'	HPS	26.8±1.1	38.1±1.2	6.1±0.2	2.30±0.15	19.0±0.3
	LED	38.4±0.8 ***	41.6±1.1 NS	6.9±0.3 *	3.54±0.23 ***	19.2±0.3 NS
Vinca 'Cora Burgundy'	HPS	9.5±0.4	17.0±0.3	3.6±0.1	0.88±0.03	18.9±0.2
	LED	14.6±0.3 ***	20.2±0.3 ***	3.5±0.1 NS	1.36±0.07 ***	19.0±0.1 NS
Zinnia 'Zahara Cherry'	HPS	12.8±0.5	22.0±0.5	4.3±0.1	1.86±0.11	18.6±0.1
	LED	18.0±0.8 ***	24.8±0.5 **	4.3±0.1 NS	3.10±0.13 ***	19.2±0.1 **

[a]NS, *, **, *** t-test nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

The relative chlorophyll content index (CCI) was 102% higher in basil; similar in pepper, spinach, and zinnia; and 14- 26% lower in vinca, tomato, pansy, and geranium, supplemented with LEDs compared to HPS (data not shown). Hernández and Kubota (2014) observed increased chlorophyll concentration in greenhouse-grown cucumber (*Cucumis sativus* 'Cumlaude') as the B:R ratio of their supplemental LED treatments increased, which is similar to our observation in basil. Conversely, Randall and Lopez (2015) reported similar relative chlorophyll content (SPAD) readings in greenhouse-grown vinca 'Titan Dark Red', impatiens (*Impatiens walleriana* 'Super Elfin XP Blue Pearl'), geranium 'Bullseye Red', and petunia (*Petunia ×hybrida* 'Dreams Midnight') supplemented with either HPS or B_{13}:R_{87} LEDs but lower SPAD readings in LED-supplemented French marigold (*Tagetes patula* 'Durango Yellow'). These studies, along with ours, indicate chlorophyll content will vary with light source but is also species and cultivar-dependent.

In LED-supplemented plants, foliar nutrient concentration of nitrogen (N) ranged from 2% higher to 14% lower, phosphorus (P) was 10% higher to 20% lower, potassium (K) was 3-32% lower, calcium (Ca) was 15% higher to 9% lower, magnesium (Mg) was 28% higher to 12% lower, sulfur (S) was 11% higher to 18% lower, boron (B) was 30% higher to 18% lower, copper (Cu) was 23% higher to 34% lower, iron (Fe) was 2-40% lower, manganese (Mn) was 13-41% lower, and zinc (Zn) was 14% higher to 31% lower, relative to HPS-supplemented plants (Tables 3 and 4). In general, plants grown under supplemental LEDs had similar or lower tissue nutrient concentrations than those grown under supplemental HPS lamps, although some species did have enhanced nutrient uptake under LED lighting for P (zinnia), Mg (pepper, spinach, and zinnia), S (zinnia), B (geranium and vinca), Cu (vinca), and Zn (vinca). Although Craver et al. (2019) evaluated different ornamental crops and at a different stage of production than in our study, they likewise observed similar or lower nutrient concentrations of most elements in seedlings grown with supplemental LED lighting compared to HPS. The differences in nutrient concentrations did not result from a C dilution effect, which has been observed in irradiance intensity studies; in the present study, %C varied ≤3% with light source in the eight species evaluated (data not shown).

Table 3. Macronutrient concentrations of 8 ornamental crops grown in a greenhouse and provided supplemental lighting from either high-pressure sodium (HPS) lamps or light-emitting diode (LED) arrays (50 blue:50 red:22 far-red) for 14 h day^{-1} at a photosynthetic photon flux density of 100 μmol m^{-2} s^{-1}.

Crop	Lighting	N	P	K	Ca	Mg	S
		(% dry mass)					
Basil 'Genovese Emily'	HPS	5.28±0.07	2.04±0.06	6.10±0.18	1.44±0.04	0.96±0.04	0.38±0.02
	LED	5.37±0.09 NS[a]	1.86±0.10 NS	5.93±0.16 NS	1.64±0.05 **	0.94±0.03 NS	0.42±0.02 NS
Geranium 'Maverick Red'	HPS	4.74±0.06	0.66±0.02	3.79±0.09	1.52±0.03	0.97±0.02	0.28±0.01
	LED	4.48±0.08 *	0.64±0.01 NS	3.45±0.04 **	1.57±0.05 NS	1.00±0.01 NS	0.28±0.01 NS
Pansy 'Delta Premium Blue Blotch'	HPS	6.48±0.11	0.98±0.05	6.11±0.10	0.97±0.04	0.69±0.03	0.44±0.01
	LED	5.57±0.12 ***	0.78±0.06 *	5.92±0.17 NS	0.88±0.03 NS	0.61±0.02 *	0.36±0.04 ***
Pepper 'California Wonder'	HPS	6.19±0.06	0.71±0.01	6.35±0.18	1.22±0.04	1.00±0.03	0.42±0.01
	LED	5.78±0.15 *	0.62±0.03 *	5.40±0.36 *	1.30±0.08 NS	1.18±0.03 **	0.43±0.04 NS
Spinach 'Whale'	HPS	6.67±0.08	1.58±0.06	7.15±0.27	0.74±0.01	1.92±0.07	0.43±0.01
	LED	6.46±0.04 *	1.47±0.05 NS	6.10±0.21 *	0.85±0.03 **	2.33±0.06 ***	0.43±0.01 NS
Tomato 'Early Girl'	HPS	6.35±0.15	1.17±0.03	5.47±0.22	1.64±0.04	1.32±0.05	0.57±0.01
	LED	5.68±0.19 *	1.04±0.06 NS	3.72±0.23 ***	1.65±0.05 NS	1.32±0.02 NS	0.58±0.03 NS
Vinca 'Cora Burgundy'	HPS	5.41±0.05	0.65±0.02	4.25±0.10	0.73±0.02	0.70±0.02	0.29±0.01
	LED	5.37±0.10 NS	0.66±0.02 NS	4.09±0.08 NS	0.79±0.02 NS	0.69±0.02 NS	0.29±0.01 NS
Zinnia 'Zahara Cherry'	HPS	5.91±0.07	1.05±0.02	6.78±0.13	0.87±0.02	0.81±0.03	0.29±0.01
	LED	5.79±0.07 NS	1.15±0.01 **	6.29±0.16 *	0.97±0.02 *	1.04±0.02 ***	0.30±0.01 *

[a]NS, *, **, *** t-test nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. Micronutrient concentrations of 8 ornamental crops grown in a greenhouse and provided supplemental lighting from either high-pressure sodium (HPS) lamps or light-emitting diode (LED) arrays (50 blue:50 red:22 far-red) for 14 h day^{-1} at a photosynthetic photon flux density of 100 μmol m^{-2} s^{-1}.

Crop	Lighting	B	Ca	Fe	Mn	Zn
		(mg kg^{-1})				
Basil 'Genovese Emily'	HPS	29.3±0.4	3.0±0.2	157.7±12.2	59.8±3.1	95.6±8.4
	LED	29.3±1.3 NS[a]	3.3±0.4 NS	102.5±2.3 ***	39.0±2.2 ***	96.9±10.5 NS
Geranium 'Maverick Red'	HPS	34.0±0.7	2.9±0.2	86.4±6.3	115.3±4.4	41.0±1.5
	LED	38.0±0.5 ***	2.4±0.1 *	72.4±1.6 *	93.4±3.1 ***	39.5±0.9 NS
Pansy 'Delta Premium Blue	HPS	28.1±1.0	3.8±0.2	115.7±4.4	178.5±12.1	127.2±4.5
Blotch'	LED	28.6±1.2 NS	2.5±0.1 ***	68.9±1.5 ***	105.8±6.0 ***	87.2±5.2 ***
Pepper 'California Wonder'	HPS	30.3±0.9	3.1±0.1	114.8±2.6	32.9±0.6	81.0±2.6
	LED	31.4±1.5 NS	3.4±0.3 NS	84.6±6.0 ***	21.8±1.8 ***	70.2±2.8 *
Spinach 'Whale'	HPS	52.3±2.1	4.8±0.3	89.3±4.0	114.0±12.7	240.1±10.5
	LED	57.5±2.4 NS	4.1±0.3 NS	82.0±2.7 NS	99.4±8.8 NS	233.2±12.9 NS
Tomato 'Early Girl'	HPS	47.8±0.6	2.1±0.1	99.7±2.8	65.7±2.3	45.0±1.2
	LED	46.4±3.1 NS	2.4±0.2 NS	98.2±6.9 NS	56.3±5.7 NS	40.6±1.8 NS
Vinca 'Cora Burgundy'	HPS	13.8±0.4	3.9±0.2	103.6±7.6	45.1±1.8	54.2±2.1
	LED	17.9±0.4 ***	4.8±0.2 **	91.7±3.4 NS	37.0±2.9 *	61.7±2.1 *
Zinnia 'Zahara Cherry'	HPS	93.0±2.8	4.8±0.2	126.5±5.9	88.8±4.0	77.6±2.2
	LED	76.5±2.4 ***	4.2±0.1 **	107.7±2.1 **	63.1±3.2 ***	74.2±2.3 NS

[a]NS, *, **, *** t-test nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

CONCLUSIONS

In summary, plant growth, morphology, and nutrient uptake differed in ornamental, vegetable, and herb species when grown under supplemental HPS or LED lighting during finished production. In this study, the addition of supplemental LED radiation resulted in taller plants with a higher dry mass, but lower tissue nutrient concentrations. However, all crops were of acceptable quality regardless of HPS or LED supplementation. Therefore, selection of light fixtures for supplemental lighting in the greenhouse should be chosen based on desired crop characteristics and associated capital and operating costs.

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